The large-scale ionized outflow of CH Cygni[1]

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ABSTRACT

HST and ground-based [O II] and [N II] images obtained in the period 1996–1999 reveal a complex, ionized optical nebula around the symbiotic binary CH Cyg extending out to 18″ or 5000 A.U. from the central stars.

The observed velocity range of the nebula, derived from long-slit echelle spectra, is 130 km s^{-1}. In spite of its complex appearance, the velocity data show that the basic morphology of the inner regions of the optical nebula is that of a bipolar outflow extending nearly along the plane of the sky out to some 2000 A.U. from the center.

Even if the extension of this bipolar outflow and its position angle are consistent with those of the radio jet produced in 1984 (extrapolated to the time of our optical imagery), no obvious optical counterpart is visible of the original, dense radio bullets ejected by the system. We speculate that the optical bipolar outflow might be the remnant of the interaction of the bullets with a relatively dense circumstellar medium.

Subject headings: binaries: symbiotic – ISM : jets and outflows – Stars: mass loss – Stars: CH Cyg

1. Introduction

One of the most debated issues in the study of the mass loss from evolved stars is the formation of collimated outflows and jets (cf. Livio 2000). In this respect, symbiotic stars are excellent laboratories to study the formation and evolution of this kind of outflows in interacting, detached bi-

[1]Based on observations obtained at the 4.2m WHT and 2.6m NOT telescopes operated on the island of La Palma by the ING and the NOTSA, respectively, in the Spanish Observatorio del Roque de Los Muchachos (ORM) of the Instituto de Astrofísica de Canarias, and with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc. under NASA contract No. NAS5-26555.

nary systems. Most of the spatially resolved nebulae known around these stars are in fact strongly aspherical (Corradi et al. 1999a), and highly collimated jets have been so far identified in several systems. They are: R Aqr (Burgarella and Paresce 1992; Dougherty et al. 1995), He 2-104 (Schwarz et al. 1989, Corradi & Schwarz 1993, Corradi et al. 2001), MWC 560 (Tomov et al. 1990; Shore et al. 1994), RS Oph (Taylor et al. 1989), BI Cru (Schwarz & Corradi 1992), Hen 3-1341 (Tomov et al. 2000), StHα 190 (Munari et al. 2001), and CH Cyg. In this last system, one of the most notable jets from a symbiotic star was detected in 1984 at λ=2 cm by Taylor, Seaquist & Mattei (1986, hereafter TSM86), who also measured its proper motions on a time basis of only 75 days.

Owing to its proximity to the Earth (Hipparcos measured a distance of 268 pc, Munari et al. 1997), in CH Cyg we have the opportunity to study in great spatial detail the structure of a stellar jet and follow its evolution in real time. With this aim, we have obtained narrowband images of CH Cyg with the HST and the Nordic Optical Telescope 12 to 15 years after the ejection of the radio jet. These images, which reveal the existence of a large ionized nebula around the symbiotic core, are presented in this paper together with ground based echelle spectra which allow us to discuss the spatiokinematical structure of the optical outflow and its orientation in the sky. The observations are detailed in §2, the images are presented in §3, and the kinematical data in §4. §5 contains a critical review of the general properties of CH Cyg, the discussion of the origin of its large-scale ionized nebula and its possible link with the 1984 radio jet.

2. Observations

[N II] and [O II] images of CH Cyg were obtained under sub-arcsec seeing conditions at the 2.6m Nordic Optical Telescope (NOT) of the ORM, La Palma, using the BroCam2 direct camera in 1996 and the ALFOSC instrument in 1997. Both cameras used a Loral 2k x 2k CCD with a scale of $0''.11$ and $0''.19$ per detector pixel, respectively. With ALFOSC, a coronographic plate was used for the longest exposure, to stop light from the bright central source and prevent saturation of the CCD. The central wavelength and FWHM of the filters used at the NOT are: [O II] (372.5/2.9 nm) and [N II] (658.9/0.9 nm). In the following, we will therefore indicate with [OII] and [NII] the emission in the nebular lines [O II]$\lambda\lambda$372.7,372.9 nm, and [N II]λ658.3 nm. Given the very similar ionization potentials of these oxygen and nitrogen ions, we will also assume that they are emitted in similar regions of the ionized nebula around CH Cyg. Exposure times and seeing are detailed in Table 1.

[O II] images of CH Cyg were also obtained with the Hubble Space Telescope in 1999, using the STIS camera and aperture F28$\times$50 OII. The [O II] filter of STIS is centered at 374.0 nm and has a FWHM of 8.0 nm. We obtained a short image of CH Cyg (200 sec split into two repeated exposures to allow for cosmics removal and limit saturation of the central source) as well as a deeper one (2508 sec split into 3 exposures). The STIS CCD pixel size is $0''.05$, and stars have a FWHM of about 1.4 pixels at the [O II] wavelengths.

The kinematics of the ionized nebula around CH Cyg was studied by means of long-slit, echelle [N II] spectra obtained in 1997 at the 2.6m NOT and at the 4.2m William Herschel Telescope (WHT) of the ORM. At the NOT, we used the IACUB spectrograph, provided with a Thompson THX31156 CCD which gives a spatial scale of $0''.14$ pix^{-1}. To increase the signal–to–noise ratio, 2$\times$2 binning was done along both the spatial and spectral directions. The projected slit width was $0''.65$, providing a spectral resolution $R = \lambda/\Delta\lambda$ =30000, with a reciprocal dispersion of 0.009 nm per binned pixel. At the WHT, we used the UES spectrograph equipped with a SIT1 CCD, providing a spatial scale of $0''.36$ pix^{-1}. The spectral resolution was R = 50000, with a reciprocal dispersion of 0.007 nm per pixel and a slit width of $1''.0$. The spectrograph slit was positioned both on the central star, and offset to cover most of the nebular features of CH Cyg. Exposure times, slit position angles and offsets are summarized in Table 1.

3. Morphology

The [N II] and [O II] images of CH Cyg are presented in Figure 1. These images reveal for the first time the existence of a large ionized nebula extending out to $18''$ (or $\sim$5000 A.U. for a distance of 268 pc) from the central stars. In its outer parts (Figure 1, top panels), the nebula is fragmentary, showing faint "plumes" in the NW quadrant and "knots" toward the East. The bright, inner body of the nebula is also complex, but generally elongated along the NW and SE directions (Figure 1, middle panels). The detailed morphology of its brightest parts is revealed by the HST images (Figure 1, bottom). Toward the NW, a collimated 'spray' of emission extends from the central stars along P.A.=$-35°$ up to a distance of $3''.2$ and possibly out to $4''.3$ (1000 A.U.), with it's width increasing with distance from $\sim$150 to $\sim$300 A.U. On the SE side, the [O II] emission in the innermost arcsecond from the central stars (inset box in Figure 1, bottom right) is elongated roughly toward the South : its properties and formation are discussed by Eyres et al. (2001). Outwards, emission bends toward the SE opening and forming arcs and knots which become fainter with distance, but which can be followed out to the peripheric zones of the nebula in the deep NOT images.

We have considered the possibility that the collimated 'spray' of emission extending NW from the central stars is an instrumental artefact, especially because it appears along the serial read axis of the CCD. To check it, we have constructed an empirical point-spread-function (PSF) using archive STIS images of a calibration star which was observed through the same [O II] filter, in the same position in the CCD chip, and only 17 days later than CH Cyg. This PSF was then subtracted from our images, after scaling its peak emission to match that of CH Cyg (note that a small scaling factor, $\sim$2, was applied in the case of our short image, which is only slightly saturated). The subtracted images are presented in Figure 1, bottom right, and in the inset box. A similar result is obtained using the PSF to restore the images with the Lucy-Richardson algorithm. In both cases, while most instrumental artefacts are significantly reduced, the NW collimated emission is instead enhanced, making us confident that it is a real nebular structure.

In the short subtracted image (Figure 1, inset box), a small ring is visible which extends out to $0''.35$ (100 A.U.) West of the center. It is not clear whether this ringlet is a real feature or the typical ghost appearing in STIS images close to bright stars (see *www.stsci.edu/cgi-bin/stis?stisid=224&cat=performance&subcat=foibles*). Together with another dubious feature, it is marked with the label "real?" in Figure 1.

HST images of CH Cyg in other filters were obtained with WFPC2 by Eyres et al. (2001). The comparison of our [O II] image with their [O III] one is especially interesting: the latter one does not show the 'spray' of collimated outflow on the NW side of the stars, nor it shows the extended 'arcs' toward the SE except for the brightest emission in the innermost $1''.5$. This confirms our previous finding (e.g. Corradi et al. 1999b) that radiation from low-ionization species such as [N II] and [O II] is likely the best tracer of large-scale outflows (i.e. several orders of magnitude larger than the binary separation) in symbiotic systems.

4. Kinematics

The slit positions of the echelle spectra covered most of the nebular features of CH Cyg. In particular, the NOT spectra provide a detailed mapping of the bright inner regions, while the WHT ones were meant to cover the faint outer structures. In all spectra, radial velocities were measured by multi-Gaussian fitting of the [N II] line profile at selected positions along the slits, and correcting for the heliocentric systemic velocity of CH Cyg of -58 km s^{-1} (Skopal et al. 1989).

The number of velocity components observed in the spectra at all slit positions reflects the morphological complexity of the nebula. Radial velocities span an overall range of 130 km s^{-1}. This is significantly larger than the velocity of a standard red giant wind, implying that fast winds or ejecta from the hot component must play a role in producing the observed nebula, and possibly also ionizes it by shock heating. The observed radial velocities, however, are also clearly lower than the total expansion of $1400/\sin i$ km s^{-1} derived for the 1984 radio jet by TSM86 using its proper motions (i is the inclination of the jet to the line of sight). Either the optical nebula is not associated with the radio ejecta, or the latter have been dramatically slowed down between 1984 and 1997, or projection effects are large, i.e. material is expanding nearly along the plane of the sky.

The velocity field of the inner nebula is shown in Figure 2. Most [N II] position-velocity plots are reminiscent of 'ellipses', albeit fragmentary and distorted. The spatial position and extent of the ellipses are indicated in the bottom panels of Figure 2, superimposed on the HST and NOT images. These kinematical figures are better seen in the SE side, where the spatial size of the ellipses also appears to increase slightly with distance from the center, suggesting that the overall outflow has a 3-D conical or bipolar geometry. It is clear that the aperture of the bipolar outflow described by the kinematical ellipses ($\sim 10^{16}$ cm) is much larger than the innermost, collimated NW 'spray', and also larger than the brightest SE 'arcs' seen in the HST [O II] image. The size of the ellipses matches instead, within the uncertainty in the spatial 'zero' point along each slit position, that of the elongated nebulosity seen in the deep NOT [O II] image (Figure 1, top right, and 2, bottom right). The sharp SE 'arcs' and the NW 'spray' of collimated emission seen in the HST image might then be surface brightness enhancements on the walls of a wider bipolar outflow. As with velocities, the analysis is limited by the irregular shape of the kinematical figures, but most ellipses have a kinematical axis of between 100 and 120 km s^{-1}, and all them are fairly well centered on the adopted systemic velocity. This latter property indicates that the axis of the bipolar outflow lies almost exactly in the plane of the sky. Under this hypothesis, and also assuming that velocities are directed radially from the central stars, deprojected expansion velocities result to be around 100 km s^{-1}, i.e. not dramatically larger than the observed ones. These are still notably lower than those of the 1984 radio jet. The kinematical age of this bipolar outflow would result to be 25 yrs for the material $1''.5$ SE of the star (400 A.U.), increasing to 75 yrs for gas at a distance of $5''$ (1300 A.U.). The figures above, however, should be taken with caution because of the several simplistic assumptions involved. If, for instance, velocities were not directed radially and gas were instead flowing along the walls of the bipolar outflow, then deprojected velocities would be much larger, and be eventually comparable with those derived from the apparent expansion of the radio jet. Kinematical ages would also be shorter, especially for gas at $\geq 3''$ SE of the center, where the flow looks almost cylindrical with the walls parallel to the plane of the sky.

The radial velocities of the faint outer nebula from the WHT spectra are indicated in Figure 3. Radial velocities in the plumes and knots span a range from -72 km s^{-1} to $+55$ km s^{-1} with respect to the systemic velocity. Again, the kinematics indicates that the geometry of the outer nebula is complex and asymmetrical, since most components are redshifted regardless of which side of the nebula they are located on. Note that this could imply reflection off these features instead of emission from them (cf. M2–9 in Schwarz et al.1997).

5. Discussion

5.1. Basic parameters of the system

Before discussing the origin of the extended nebula of CH Cyg, some discussion about the basic properties of its central stars is in order. CH Cyg (HD182917 = HIC 95413) is one of the best studied symbiotic stars, with ∼550 publications related to it. Before 1963, it was known as a low amplitude variable with a weak periodicity around 100 days and no spectral peculiarities; CH Cyg was in fact adopted as a standard star for the spectral type M6III in the MKK system. Starting in 1963, the presence of a hot companion was revealed by the sudden appearence of emission lines, a marked brightening in the blue and UV, and irregular flickering at short wavelengths with a large amplitude and timescale of minutes (Deutsch 1964, 1967; Cester 1969; Walker et al. 1969). CH Cyg was consequently reclassified as a symbiotic star.

This first outburst ended in 1970, and was followed by a longer and more pronounced one (V up to 5.5 mag) lasting from 1977 to 1986, which was widely studied at all wavelengths. Toward its end, in the summer of 1984, the drop in brightness and the disappearance of the enhanced blue/ultraviolet continuum was accompanied by the ejection of a high velocity radio jet and a sudden broadening of the emission lines (Tomov 1984, Selvelli & Hack 1985, TSM86). In the following years, the brightness of CH Cyg remained close to quiescent levels with moderate re-brightenings in 1993-1994 and 1998-2000 (Taranova & Shenavrin 2000).

As with the cool component of CH Cyg, the study of the UBV lightcurve from 1885 to 1988 (Mikolajewski et al. 1990) and of JHKLM photometric data for the last 25 yrs (Munari et al. 1996, Taranova & Shenavrin 2000) have revealed the following properties: *i)* low-amplitude optical and near-IR variability with several periodicities (100, 770 1300, and 1980 days); *ii)* a secular decrease in the mean luminosity of the red giant ($\triangle V \geq 3-4$ mag over 120 yrs, with a rapid acceleration in the last 40 yrs); *iii)* variable obscuration from several episodes of dust condensation in the giant wind; and *iv)* infrared properties typical of the bulge/thick-disk population of the Galaxy, favouring a red giant mass around 1 $M_{\odot}$.

The hot component of CH Cyg is quite unusual for symbiotic stars, having never reached temperatures ≥100,000 K that power the typical high ionization emission line spectrum of symbiotic stars. During activity, the IUE ultraviolet spectrum of CH Cyg resembles that of an A star (Hack & Selvelli 1982), although no model atmosphere gives an acceptable fit to the erratically variable UV continuum. At quiescence, the UV continuum resembles instead that of a moderately hot (∼35,000 K) white dwarf (e.g. Mikolajewska et al. 1993). In spite of the relatively low temperature of its hot component, CH Cyg shows strong X-ray emission which is variable at long and short timescales, and has two main broad components peaking at 0.8 keV and at 4-5 keV both originating in optically thin hot plasma (Ezuka et al. 1999, see also Leahy & Taylor 1987 and Murset et al. 1997).

A robust distance determination for CH Cyg was provided by Hipparcos: d = 268 pc ±23% (Munari et al. 1997). Its large barycentric radial velocity supports the association of CH Cyg with the spheroidal or thick-disk component of the Galaxy as suggested by the infrared properties.

The most accepted orbital period for the CH Cyg symbiotic system is around 15.5 yrs with hints of an eclipsing nature (Mikolajewski et al. 1990), although some debate has been raised in recent years following the claim by Hinkle et al. (1993) that the system might be triple, with 2 and 15.5 yrs orbital periods, a claim not supported by the analysis of Munari et al. (1996).

5.2. The origin of the optical nebula

Prior to our observations, the only evidence for spatially resolved outflows from CH Cyg was the spectacular radio jet discovered by TSM86, subsequent radio imagery by Crocker et al. (2001), and the optical spectroscopy of Solf (1987) and Tomov et al. (1996) limited to the innermost arcsecond. With our optical data, in principle we have the opportunity of exploring how the jet has evolved 12 to 15 years after its production. According to the expansion rate measured by TSM86 ($0''.55$ yr^{-1} on each side of the central star), at the time of our optical imagery the jet should have reached a distance from the central source of $7''$ (1996 and 1997, NOT imaging) and $8''$ (1999, HST images), i.e. large enough to be easily resolved even in our ground-based images (see the crosses in Figure 1, top/middle-right and bottom-left, and in Figure 3).

Following TSM86, the jet was essentially made up of two components, each with a size of $\sim 10^{14}$ cm and a density $\geq 2 \times 10^6$ cm^{-3}. Because of the interaction with the ambient medium and the radiation field, such supersonic, dense 'bullets' will expand, and eventually will be fragmented and disrupted by Kelvin–Helmholtz and, more importantly, by Rayleigh–Taylor instabilities. The disruption timescale can be estimated using the formulae in Jones, Kang, & Tregillis (1994) and Klein, McKee, & Colela (1994). For environmental densities of $\sim 10^2$ cm^{-3}, i.e. a density contrast with the jet of 10^4, the time at which half of the bullet material will be mixed up with the ambient medium is on the order of 80 yr. For larger environmental densities, namely $\sim 10^3$ cm^{-3} and $\sim 10^4$ cm^{-3}, the timescales are 30 yrs and 8 yrs, respectively. In the same time interval, the bullets are expected to be slowed down by ram pressure only by some 25% of their initial speed. Considering the figures above, and all the uncertainties in the physical parameters of the jet and the ambient medium (especially the density of the latter which is presently not known), we cannot therefore rule out completely the possibility that at the time of our optical imaging the radio jet has been disrupted and has mixed up with the circumbinary gas. Environmental gas densities of more than 10^3 cm^{-3} are in fact possible in the inner circumbinary regions. This might be the reason why no obvious optical counterpart of the original bullets of the radio jet is seen in our optical images. Note that VLA radio maps at λ=2 cm taken on March 20, 1986, i.e. 1.2 yr after the images of TSM86, show the bullets at approximately the correct position as predicted according to their expansion rate, while they are not visible any longer in maps taken another 2.6 yrs later (Crocker et al. 2001).

There are, however, nebular structures which might be linked with the evolution of the radio jet. The symmetry axis of the inner bipolar outflow of CH Cyg discussed in the previous section is in fact oriented as the radio jet along P.A.$\sim -45°$. Also the overall size of this bipolar outflow (Figure 1, top-right) is roughly the one expected by extrapolating the proper motions of the 1984 radio jet. We tentatively propose that the optical bipolar nebula might be the result of the interaction of the original dense bullets with the circumstellar gas and radiation field from the hot component. Although the details of the process might be complex, it is clear that the high velocity bullets will sweep up the circumstellar material in the direction of their motion forming large bow-shocks, and at the same time will expand, dilute, and be disrupted by dynamical instabilities (cf. also Mellema et al. 1998; Soker & Regev 1998). Some of the features seen in the [O II] HST image (such as the inner 'arcs' and 'spray') might in fact be tentatively associated with such instabilities. Detailed models are needed to test whether these processes together can produce, with the correct space and time scales, the bipolar 'cavity' observed in the optical forbidden lines in CH Cyg.

Whatever is the relation between the radio jet and the optical nebula, our spatiokinematical analysis indicates that the bipolar outflow of CH Cyg lies almost exactly in the plane of the sky. As CH Cyg is an eclipsing binary, i.e. the orbit is seen edge-on, our results are fully consistent with the idea of a *polar* outflow. This is an important finding, since albeit predicted by theories (e.g. Morris 1987, Soker 1997), direct evidence that collimated outflows from wide interacting binaries occur along the polar direction of the orbits can hardly be found.

6. Summary and conclusions

The HST and NOT narrowband images and spectra of CH Cyg have revealed a complex, ionized nebula around this enigmatic symbiotic system, which extends 5000 A.U. from the central system and has an observed velocity range of 130 km s^{-1}. The spatiokinematical analysis suggests that the kinematical age of the whole nebula (including the outermost plumes and knots) is certainly < 100 yrs, and possibly much lower.

In the optical images, no obvious counterpart of the radio bullets ejected 12-15 yrs before is visible, but we tentatively interpret the observed bipolar optical outflow as being the remnant of the interaction of the original jet with a relatively dense circumstellar medium, based on the fact that their projected alignment is the same and the size of the optical outflow is consistent with the proper motions originally measured for the radio bullets. Further imagery over the next years will be important to test this hypothesis and better understand the evolution of such a short-lived, nearby stellar jet.

The data are also consistent with the idea of a collimated flow along the polar axis of the orbit. The determination of the position angle in the sky of the binary axis of CH Cyg, e.g. by means of spectropolarimetric observations (cf. Schmid et al. 2000), would finally confirm it.

ML acknowledges support from NASA Grant GO 7378 from the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA contract NAS 5-26555. The work of AM, DRG and RLMC is supported by the Spanish grant DGES PB97-1435-C02-01.

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Fig. 1.— The NOT and HST images of CH Cyg, on a logarithmic intensity scale. North is at the top, East to the left: in order to have this orientation, the original HST images have been rotated counterclockwise by 54° . Details of the nebular core are given in the inset box at the bottom right, which is enlarged ×2 compared to the other HST images. In the NOT and HST [O II] images (top/middle-right and bottom-left), we have marked with crosses the positions at which the 1984 radio jet would be expected at the epoch of our optical imagery, according to the proper motions measured by TSM86.

Fig. 2.— At center, the location of the slits for the NOT spectroscopy. Above and below it, the [N II] spectra, on a logarithmic scale unless otherwise indicated. The spatial direction is the vertical one (the size of each box is 15 arcsec, and corresponds to the size of the slits drawn over the image), while wavelengths increase along the horizontal direction. At bottom, the ellipses drawn onto the [O II] HST and NOT images represent the location and extent of the kinematical ellipses outlined by the spectra (see text).

Fig. 3.— The observed radial velocities, as derived by Gaussian fitting in the WHT spectra and corrected for the systemic velocity, for the faint outer features of the nebula of CH Cyg.

Table 1: Log of the observations

Images

Instrument	date	filter	exp. time (sec)	seeing
NOT+Brocam2	4.6.1996	[N II]	20, 90, 300, 1200	0″.6-0″.8
NOT+ALFOSC	14.7.1997	[O II]	60, 240×5, 1800C⋆	1″.0
HST+STIS	1.10.1999	[O II]	200, 2508	

⋆ C = Coronographic plate

Long–slit spectra

Instrument	date	P.A.(°)	offset*	exp. time	seeing
WHT+UES	10.7.1997	+45	centered	600	2″.0
		−40	1.1*W*, 1.0*S*	1800	
		−50	3.9*W*, 4.6*S*	2400	
		+30	8.5*W*, 7.0*N*	2000	
		+45	2.1*E*, 2.1*S*	900	
		+45	3.0*E*, 3.0*S*	1200	
		+5	10.5*W*, 0.9*N*	1800	
		+60	1.9*W*, 3.2*N*	1200	
		+95	1.0*E*, 11.5*S*	2400	
NOT+IACUB	17.7.1997	+45	2.8*N*, 2.8*W* (**a**)	600	0″.7
		+45	2.1*N*, 2.1*W* (**b**)	1800	
		+45	1.4*N*, 1.4*W* (**c**)	900	
		+45	0.7*N*, 0.7*W* (**d**)	1800	
		+45	0.7*S*, 0.7*E* (**e**)	900	
		+45	1.4*S*, 1.4*E* (**f**)	900	
		+45	2.1*S*, 2.1*E* (**g**)	1200	
		+45	3.0*S*, 3.0*E* (**h**)	1800	
	18.7.1997	+45	3.8*S*, 3.8*E* (**i**)	1800	0″.7

*Slit offsets are given in arcseconds from the central star toward North (*N*), South (*S*), East (*E*), or West (*W*). The characters in boldface are labels used in Figure 2. Seeing values are FWHM and are measured directly from the images or spectra.